Description

Method for pre-filtering training sequences in a radio
communication system

The invention relates to a method for pre-filtering training
sequences in a radio communication system, in which an antenna
arrangement comprising a number of antenna systems is used on
the transmit side at least.

In the case of radio communication systems, such as mobile
radio communication systems, to increase data transmission
capacity, antenna arrangements each comprising a number of
antenna systems are used on both the transmit side and the
receive side. Such radio communication systems are referred to
as so-called Multiple Input Multiple Output or MIMO radio
communication systems.

Special signal processing algorithms are used to split a
digital input data stream into data sub-streams and emit them
via the transmit-side antenna systems. Spatial radio channel
coefficients can be derived based on the spatial arrangement
of the antenna systems, representing characteristics of radio
transmission channels. The radio channel coefficients for
example describe signal fading, specific propagation,
attenuation, interference, etc. in the radio transmission
channel.

The radio channel coefficients are used for example on the
transmit side to pre-filter the data sub-streams, to adjust
these in an optimum manner to the radio transmission in
respect of a higher data throughput or in respect of a higher
level of transmission quality. For example pre-filtering

brings about an individual transmit power adjustment and/or an individual modulation for every data sub-stream.

In the case of a MIMO radio communication system, radio channel coefficient determination with the aid of channel estimation is very complex. With a number M_{TX} of transmit antennae and a number M_{RX} of receive antennae, a total of M_{RX} x M_{TX} radio channel coefficients to be estimated therefore results for M_{RX} x M_{TX} radio transmission channels. Specifically, for a MIMO radio communication system with four transmit and four receive antennae, a total of 16 radio transmission channels results described by 16 radio channel coefficients.

In the case of an FDD (Frequency Division Duplex) radio communication system in particular, precise estimation of the radio channel coefficients requires long training sequences, which in turn take up a considerable number of radio transmission resources.

The object of the invention is therefore to implement an estimation of radio channel coefficients involving little outlay and with greater precision in a radio communication system, in particular in a MIMO radio communication system.

The object of the invention is achieved by the features of claim 1. Advantageous developments are set out in the subclaims.

The claimed pre-filter is arranged on the transmit side before an antenna arrangement such that training sequences are fed via the pre-filter to antenna systems in the antenna arrangement for emission. Channel estimation takes place based on the training sequences to determine radio transmission

channel characteristics, which are described by spatial
correlations. The pre-filter is dimensioned as a function of
the spatial correlations such that a predefined error value of
an algorithm used on the receive side for channel estimation
is achieved.

This receive-side error value is for example predefined as an
error value to be minimized or a predefined error value is to
be achieved by means of a variation in the length of the
training sequences.

The radio transmission channel characteristics are estimated
on the receive side with the aid of the training sequences and
transmitted to the transmit side for dimensioning the pre-
filter. This is the case for example when different carrier
frequencies are used for radio transmission in the uplink and
in the downlink.

Otherwise the radio transmission channel characteristics are
determined on the transmit side as a function of a
transmission method used. This is the case for example when
different time slots of a carrier frequency are used for radio
transmission in the uplink from a mobile station to a base
station and in the downlink from a base station to a mobile
station. As in this case there is essentially no difference
between the radio transmission channel characteristics in the
uplink and in the downlink, the radio transmission channel
characteristics can be determined directly on the part of the
base station from the uplink and are therefore available
directly to the base station on the transmit side.

The pre-filter embodied according to the invention allows
better channel estimation than a radio communication system

without pre-filtering. The improvement is achieved in respect of the mean squared error in particular when an algorithm is used on the receive side to form a mean squared error value, referred to as an MSE algorithm. It also allows the use of shortened training sequences in compliance with a predefined error value.

The fact that the training sequences can be shortened for a predefined error value with the aid of the claimed pre-filter means that radio transmission resources can be saved, advantageously making them available for payload transmission.

The outlay required to estimate the radio channel coefficients is reduced and the estimation is simplified, as on the one hand only static information with long-term stability relating to the spatial correlation conditions for every radio transmission channel or antenna system is used for pre-filtering or channel estimation. On the other hand the outlay required for the channel estimation calculations is reduced by the use of shortened training sequences.

Pre-filter dimensioning should particularly advantageously only be carried out at fairly long time intervals based on the slow change in radio channel coefficients.

When estimating the radio channel coefficients, influences affecting the radio transmission channel, e.g. fading, are taken into account.

The claimed method for pre-filtering can also be used with so-called Multiple Input Single Output MISO radio communication systems as well as MIMO radio communication systems.

In the case of a MISO radio communication system, a number of transmit antenna systems, in some instances operated as an intelligent antenna arrangement or smart antenna, are used on the transmit side, while only a single antenna system is arranged on the receive side.

The claimed method is advantageously based on the knowledge that in the case of a typical free space propagation the radio transmission channels or the transmit or receive antenna systems assigned respectively to the radio transmission channels are correlated spatially in respect of each other. This means that the radio channel coefficients have to be determined precisely in particular with a direct free line of sight, as they only change over quite a long observation period.

For a better understanding of the invention a typical MIMO radio communication system is shown below in a general form by way of an example.

Figure 1 shows a block circuit diagram of a MIMO radio communication system. A digital input signal IN, having serially consecutive bits, reaches a serial/parallel converter SPW on the transmit side, with the aid of which the input signal IN is split into a total of MT data sequences D11, D12, …, D1MT for MT transmit-side sub-channels SU11, SU12, …, SU1MT. Each individual MT transmit-side sub-channel SU11 to SU1MT has a modulator QMOD to modulate the individual data sequences D11 to D1MT, with the data sequences D11 to D1MT being modified here with the aid of an identical modulation method.

Modulated data sequences DM11, DM12, …, DM1MT pass via a pre-filter FS for emission to a transmit-side antenna unit ATN1Z, having a total of MZ individual antenna systems A11, A12, …, A1MZ. A receive-side antenna unit ANT2Z, having a total of MR individual antenna systems A21, A22, …, A2MR, is used to receive MR data sequences DZ21, DZ22, …, DZ2MR. These each have a noise element, represented by a noise vector n.

The MR data sequences DZ21 to DZ2MR reach a matrix filter GE, which forms MT data sequences D21, D22, …, D2MT for MT receive-side sub-channels SU21, SU22, …, SU2MT. The data sequences D21 to D2MT reach a parallel/serial converter PSW, which forms an output signal OUT with serially consecutive bits. The characteristics of the transmission channels can be combined as radio channel coefficients in a matrix.

The claimed pre-filtering is derived by way of an example below for an algorithm used on the receive side to form a minimum mean squared error value or MMSE algorithm.

It is assumed that the transmit-side training sequences are fed orthogonally in respect of each other to the transmit-side pre-filter for pre-processing.

The following abbreviations are used below:

I	designates a unit matrix
M^*	designates a conjugated complex matrix M
M^T	designates a transposed matrix M
M^H	designates a conjugated transposed matrix M (hermitian matrix)
$[M]_{ij}$	designates an element of a line i and a

column j of a matrix M

vec(M)   forms a vector from columns of a matrix M

$\otimes$ designates a Kroneck product

diag(M)=diag(M)^T forms a diagonal·matrix with elements x⁻on⁻

the diagonal

In the case of a MIMO radio communication system a transmission of a training sequence via a radio transmission channel with white noise at the receiver is modeled by:

$$Y = R_{\tilde{n}\tilde{n}}^{-0,5} HFS + R_{\tilde{n}\tilde{n}}^{-0,5} \tilde{N} = R_{\tilde{n}\tilde{n}}^{-0,5} HFS + N$$

Equation (1)

where:

N_t is the training sequence length,

M_{Tx} is the number of antenna systems on the transmit side,

M_{Rx} is the number of antenna systems on the receive side,

S   is the transmit-side training sequence matrix for the variable M_{Tx} x N_t,

F   is the linear matrix of the transmit-side pre-filter, variable M_{TX} x M_{TX},

H   is the radio transmission channel matrix with correlated radio channel coefficients, variable M_{TX} x M_{RX},

$\tilde{N}$ is the measured receive-side noise matrix before a "noise-whitening" noise filter, variable M_{Rx} x N_t,

N   is the receive-side noise matrix with white noise after the "noise-whitening" noise filter, variable M_{Rx} x N_t,

$R_{\widetilde{n}\widetilde{n}}$ is the estimated noise covariance matrix according to equation (5),

Y   is the measured, noisy, receive-side training sequence matrix, variable M_{Rx} x N_t.

In the case of orthogonal training sequences, the transmit-side training sequence matrix S satisfies the following condition for a discrete Fourrier transformation matrix or DFT matrix:

$$SS^H = S^H S = N_t \cdot I$$

Equation (2)

If we break the noise matrix $\widetilde{N}$ down into column vectors where:

$$\widetilde{N} = \left[\widetilde{n}_1, ..., \widetilde{n}_{N_t}\right]$$

Equation (3),

then the noise covariance matrix $R_{\widetilde{n}\widetilde{n}}$ in equation (1) is as follows as the expected value E where $1 \leq i \leq N_t$:

$$R_{\widetilde{n}\widetilde{n}} = E\left[\widetilde{n}_i \widetilde{n}_i^{H}\right]$$

Equation (4)

The covariance matrix of the columns of the noise matrix N in equation (1) assumes the value of the unit matrix I for white Gaussian noise.

An estimation of the radio channel coefficients is considered below using the receive-side MMSE algorithm and using the pre-filter assumed to be known.

To this end equation (4) is converted to a vector notation:

$$\underbrace{vec(Y)}_{y} = \underbrace{((FS)^{T} \otimes R_{\widetilde{n}\widetilde{n}}^{-0,5})}_{X} \cdot \underbrace{vec(H)}_{h} + \underbrace{vec(N)}_{n}$$

$$y = X \cdot h + n$$

Equation (5),

where h, n, y are column vectors.

If the column vectors h, n have the covariance matrices R_{hh} and R_{nn}, a linear MMSE channel estimation of the column vector h is carried out according to an equation known from the publication "Fundamentals of statistical signal processing volume 1 (estimation theory)", Kay S. M., Prentice Hall, 1993.

The following estimated value results for the column vector h:

$$\hat{h} = (R_{hh}^{-1} + X^H R_{nn}^{-1} X)^{-1} X^H R_{nn}^{-1} y$$

Equation (6)

where R_{hh} is the covariance matrix of the column vector h and R_{nn} is the covariance matrix of the column vector n.

As shown below, the matrix X is a function of the covariance matrix R_{hh}. In the case of white noise the covariance matrix R_{nn} assigned to the column vector n corresponds to the unit matrix I.

A simplified model of a correlated MIMO radio transmission channel is known from the publication "Fading correlation and its effect on the capacity of multielement antenna systems", Shiu, Foschini, Gans, Kahn, *IEEE Transactions on Communications*, vol. 48, no.3, pp.502-513, March 2000.

The following thereby applies by way of an example for both the transmit-side and receive-side correlation of antenna systems or radio transmission channels for the radio transmission channel matrix H:

$$H = A^H H_W B$$

Equation (7)

$$AA^H = R_{Rx}$$

Equation (8)

$$BB^H = R_{Tx}$$

Equation (9)

where:

AA^H is the matrix root, defined using R_{Rx},

BB^H is the matrix root, defined using R_{Tx},

H_W is the complex radio transmission channel matrix with Gaussian variables of a unit variance, variable $M_{Rx} \times M_{Tx}$,

H is the radio transmission channel matrix with correlated radio channel coefficients, variable $M_{TX} \times M_{RX}$,

R_{Rx} is the standard receive-side correlation matrix with long-term stability with radio channel coefficients, variable $M_{Rx} \times M_{Rx}$, and

R_{Tx} is the standard transmit-side correlation matrix with long-term stability with radio channel coefficients, variable $M_{Tx} \times M_{Tx}$,

The following results when using the channel model specified above:

$$R_{hh} = R_{Tx}^* \otimes R_{Rx}$$

Equation (10)

With the specified channel model[12] a mean squared error value MSE ε is derived:

$$\varepsilon = tr((R_{Tx}^*)^{-1} \otimes R_{Rx}^{-1} + N_t(F^*F^T \otimes R_{\tilde{n}\tilde{n}}^{-1}))^{-1}$$

Equation (11)

Trace has hereby been abbreviated to "tr".

Assuming that statistical information is available about radio channel coefficients on the transmit side and receive side, taken into account as R_{Tx} and R_{Rx} in equation (11), a linear pre-filter F can be proposed correspondingly, taking into account a minimum error ε.

Additive superimposition with white Gaussian noise at the receiver is considered below and a closed solution is derived for the MMSE algorithm.

The following applies:

$$R_{\tilde{n}\tilde{n}} = N_0 \cdot I$$

Equation (12),

where N_0 is the noise power.

This gives an error value ε of:[13]

$$\varepsilon = tr((R_{Tx}^*)^{-1} \otimes R_{Rx}^{-1} + \frac{N_t}{N_0}(F^*F^T \otimes I))^{-1}$$

Equation (13).

Based on this equation the claimed pre-filter is proposed below for different propagation scenarios.

On the one hand the transmit-side pre-filtering and optimum adjustment of the training sequences to the radio transmission channel allow a better estimation of the radio channel coefficients and on the other hand it is possible to shorten the transmit-side training sequences with a predefined error value ε.

Eigenvalue decomposition is carried out below with the eigenvalues Λ_{Rx} and Λ_{Tx}. The following applies:

$$R_{Rx} = V_{Rx}\Lambda_{Rx}V_{Rx}^H$$
$$R_{Tx}^* = V_{Tx}\Lambda_{Tx}V_{Tx}^H$$

Equation (14)

where

R_{Rx} is the receive-side correlation matrix,

R_{Tx} is the transmit-side correlation matrix,

V_{Rx} is the eigenvectors (v_{R1}, v_{R2}, ..., $v_{R,MRx}$) of the receive-side correlation matrix R_{Rx},

V_{Tx} is the eigenvectors (v_{T1}, v_{T2}, ..., $v_{Tx,MTx}$) of the transmit-side correlation matrix R_{Tx},

Λ_{Rx} is the eigenvalues (Λ_{R1}, Λ_{R2}, ..., $\Lambda_{R,MRx}$) of the receive-side correlation matrix R_{Rx}, and

Λ_{Tx} is the eigenvalues (Λ_{T1}, Λ_{T2}, ..., $\Lambda_{T,MTx}$) of the transmit-side correlation matrix R_{Tx}.

An eigenvalue Λ_{Ti} ($i=1$, ..., M_{Tx}) with an assigned eigenvector V_{Ti} ($i=1$, ..., M_{Tx}) should be designated as a so-called "long-term eigenmode" of the radio transmission channel, as long-term characteristics relating to the correlation are described here. A large eigenvalue relating to an average power to be transmitted thereby identifies a strong eigenmode.

The transmit-side training sequence matrix S and the transmit-side eigenvectors V_{Tx} can be described respectively line by line as:

$$S = \begin{bmatrix} s_1 \\ s_2 \\ \\ s_{M_{TX}} \end{bmatrix} \quad V_{TX}^{*} = \begin{bmatrix} v_1 & v_2 & & v_{M_{TX}} \end{bmatrix}$$

Equation (15)

The claimed pre-filter is described by:

$$F^* = V_{Tx}\Phi_f$$

Equation (16)

where Φ_f is the diagonal matrix, by means of which transmit power is assigned to the eigenmodes or training sequences to be transmitted.

The following therefore applies for pre-filtering the training sequences:

$$F \cdot S = V_{Tx}^* \Phi_f S$$

Equation (17)

This equation on the one hand describes an assignment of power to the training sequences, carried out with the aid of the vector Φ_f, and on the other hand beam forming, carried out in respect of the training sequences with the aid of the eigenvectors V_{Tx}^* of the transmit-side correlation matrix R_{Tx}.

A sequence of transmit vectors defined in a matrix T_k is emitted via the transmit antennae for a training sequence s_k. The following applies:

$$T_k = \Phi_k V_k s_k$$

for all k.

Equation 18

Equation (18) can be interpreted as the beam forming of a training sequence s_k with an eigenvector v_k, with a power Φ_k being assigned to the training sequence s_k.

The following results from equation (13) for the error value ε:

$$\varepsilon = tr(\Lambda_{Tx}^{-1} \otimes \Lambda_{Rx}^{-1} + \frac{N_t}{N_0}(V_{Tx}^H F^* F^T V_{Tx} \otimes I))^{-1}$$

Equation (19)

The following results for the error value ε with the diagonal

$$\varepsilon = tr(\Lambda_{Tx}^{-1} \otimes \Lambda_{Rx}^{-1} + \frac{N_t}{N_0}(\Phi_f \Phi_f^H \otimes I))^{-1}.$$

matrix Φ_f for transmit power assignment:

Equation (20)

In a first exemplary embodiment both a receive-side and a transmit-side correlation of the antenna systems or radio transmission channels is considered below.

The error value ε from equation (20) is minimized below with the aid of the transmit-side pre-filter. Assuming a power restriction, the following optimization problem results:

$$\underset{\Phi_f}{\underbrace{\min}} \; tr\left(\Lambda_{Tx}^{-1} \otimes \Lambda_{Rx}^{-1} + \frac{N_i}{N_0}\left(\Phi_f \Phi_f^{H} \otimes I \right) \right)^{-1}$$

(Equation 21),

with the secondary condition of the power restriction being defined by ρ where:

$$\rho = \sum_{l=0}^{M_{Tx}} \Phi_{f,l}^2$$

Equation (22)

The error value is minimized taking into account the secondary condition by means of numerical calculation and optimization methods.

In a second exemplary embodiment a solely transmit-side correlation of the antenna systems or radio transmission channels is considered below. This example describes a typical

scenario in a cellular radio communication system with a free-standing antenna arrangement.

In matrix notation the following applies for elements of the diagonal matrix Φ_f :

$$\Phi_f = \left[\frac{1}{M_{Tx}}\left(\left(\frac{N_t}{N_0}\right)^{-1}tr(\Lambda_{Tx}^{-1})+\rho\right)\cdot I - \left(\frac{N_t}{N_0}\right)^{-1}\Lambda_{Tx}^{-1}\right]^{0,5}$$

Equation (23)

with the secondary condition that all elements of the diagonal matrix Φ_f are greater than 0. This can be ensured for example by using an iterative method.

In a third exemplary embodiment a solely receive-side correlation of antenna systems is considered below.

The result is that all the elements of the diagonal matrix Φ_f are of the same order. The following applies:

$$\Phi_f = \rho \; / \; M_{Tx} \; I$$

Equation (24)

In this special case there is only undirected transmission without beam forming.